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A meta-analysis of soil background N_2O emissions from croplands in China shows variation among climatic zones

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ABSTRACT

Nitrous oxide (N_2O) is one of the most important and persistent greenhouse gases, however, there is a lack of accurate data on soil background N_2O emissions (BNE) from agricultural land. Calculations of N_2O emission factors from land uses are currently based on a single, universal BNE value advocated by the International Panel on Climate Change, but BNE are thought to vary with climate and soil types. We ran a meta-analysis of 58 peer-reviewed, published data source on soil BNE from cropland fields across China, representing a range of climate and soil types. Mean soil BNE rate in croplands was estimated at 0.93 kg N ha^{-1} yr^{-1} and varied among the climatic zones, where the highest rate was in the north subtropical zone (1.66 kg N ha^{-1} yr^{-1}) and the lowest in the cold temperate zone (0.53 kg N ha^{-1} yr^{-1}). We estimated total national BNE for China based on the BNE rates for the different climatic zones and found it to be 129 Gg N yr^{-1}; this estimate was higher than the estimate of 114 Gg N yr^{-1} derived from using only a single national average BNE rate. Stepwise multiple regression modelling of soil BNE rate (kg N ha^{-1} yr^{-1}) with soil properties and climatic parameters, including soil bulk density, mean annual precipitation, soil total nitrogen, and soil pH showed that soil bulk density had the greatest influence on the BNE rate. Our study highlights that soil BNE should be included in regional N_2O inventories to inform sustainable agricultural development and management strategies in the context of mitigating impacts of soil N_2O emissions on climate change.

1. Introduction

Nitrous oxide (N_2O) is one of the most important and persistent greenhouse gases (IPCC, 2007) and one molecule of N_2O has a global warming potential (GWP) 265 times greater than a molecule of carbon dioxide (CO_2) on a 100 year horizon (IPCC, 2013). Activities associated with agricultural development and management practices, such as clearance of semi-natural habitat and nitrogen (N) additions, are major sources of N_2O emissions from farmland (Akiyama et al., 2005; Stehfest and Bouwman, 2006; Smith et al., 2008; Zaman and Nguyen, 2012; Zaman et al., 2013). Global N_2O emissions from agricultural activities have been estimated to be 3.8–6.8 Tg N yr^{-1}, accounting for 25–39% of the total global emissions of N_2O (UNEP, 2013) and, in an effort to achieve food security for the growing global human population, intensification of agriculture is likely to result in further increases in N_2O emissions (Smith et al., 2001; Zhou et al., 2017). Indeed, it has been projected that greater amounts of synthetic N fertilizers will be required to meet the increasing food demands of a global population of 9 billion people by 2050 (Mueller et al., 2012), which, together with an increase in livestock production, may result in increases in N_2O emissions of 35–60% by 2030 (FAO, 2003).

Factors that control N_2O emissions have been reviewed (e.g. Stehfest and Bouwman, 2006; Chen et al., 2008; Jiang et al., 2010; Chen et al., 2014; Zhang et al., 2015), however, data on quantification of background N_2O emissions (BNE) from soils remain incomplete, causing controversies in the application of IPCC guidelines for the

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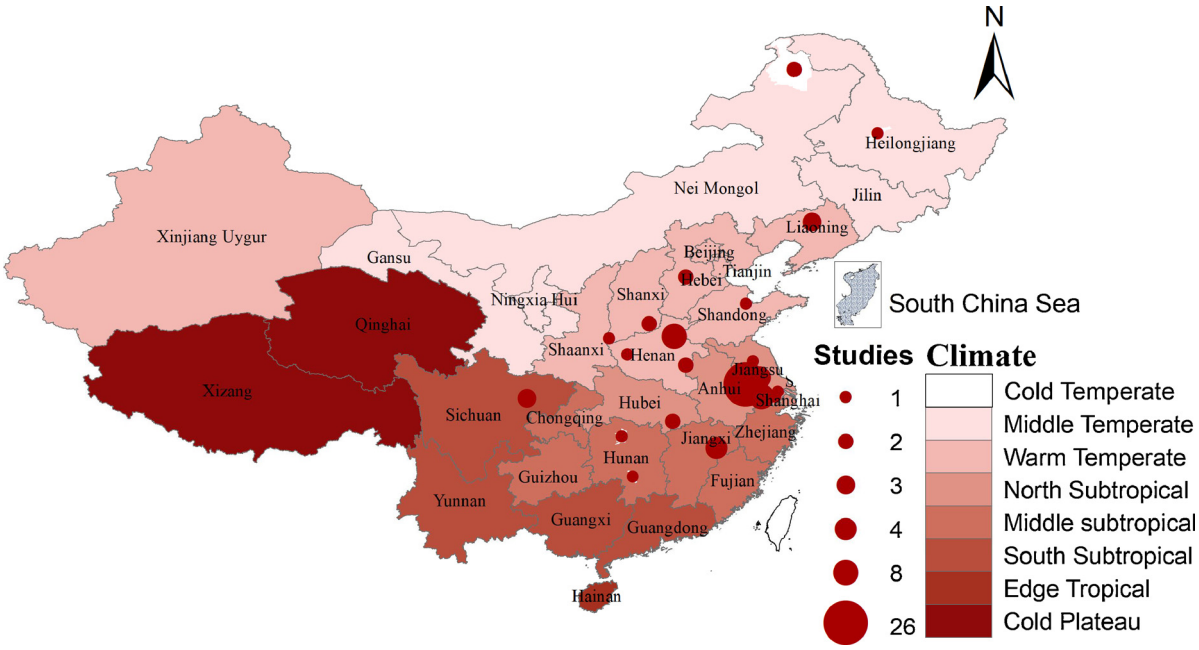

Fig. 1. Location and number of field measurements in China.

calculation of N_2O emission factors (EFs) (de Klein et al., 2010). The IPCC guidelines for the calculation of fertilizer induced total N_2O EFs are based on a single default value for BNE rate (IPCC, 2006), but this constant value for BNE rate may not account for its variability among soil types, climate conditions, agricultural management approaches, and measuring techniques, leading to discrepancies in estimated and predicted N_2O emissions at regional and global scales (Lesschen et al., 2011). These concerns are supported by recent studies that reported that the IPCC default values are unrealistic for China (Zheng et al., 2004; Zou et al., 2005; Tang et al., 2006; Song et al., 2009; Tian et al., 2012; Zhu et al., 2013), and Europe and the United States (Corazza et al., 2011; Griffis et al., 2013).

The IPCC default value for BNE rate, 1.0 kg N_2O-N ha^{-1} yr^{-1}, was based on estimates from five unfertilized field sites (Bouwman, 1996) and has been used in the estimation of regional BNE rates from cultivated cropland (Li et al., 2001). Factors that influence BNE rates in agricultural land and natural and semi-natural habitats vary among climatic zones and interactions among the factors tend to be complex and multidirectional (Kim et al., 2013), where climate change may lead to variable increases in BNE rate (Kim et al., 2012). Unlike in non-agricultural land, BNE rates from agricultural fields may reflect levels of residual N from fertilizers added in preceding years (Gu et al., 2009). Since BNE is one of the most critical contributors to N_2O emissions from agricultural land (Yan et al., 2003; Akiyama et al., 2005), it is likely that an increased number of estimates of BNE rates, representing a range of soil types, climates, and management approaches, will improve the accuracy of calculations of N_2O EFs derived from applied N (Shepherd et al., 2015).

As a national priority in China, achieving food security has driven rapid growth in fertilizer use over the past three decades, where it accounts for 30% of global use (54.3 million t) and within this, 70% of N fertilizer is applied as urea (IFADATA, 2014), partly due to fruit and vegetable production demands (Patrick, 2016). N_2O emissions associated with N fertilizer use in China are likely to be significant, but calculations of N_2O EFs may not be accurate due to variations in BNE compared with the default IPCC value (IPCC, 2006). Although BNE from agricultural soils in China has also been estimated in the previous studies, most of these estimates from croplands were calculated using the single IPCC default value for BNE (Bouwman, 1996; Gu et al., 2007; Gao et al., 2011). To date, the number of BNE measurements in China has increased four times from 15 in 2006 to 58 in 2017, which provides more insight into the estimation and prediction of N_2O emissions (Helgason et al., 2005). Here, we reviewed and evaluated the influences of climate and local farm management practice on BNE in China from peer-reviewed, published research. The objectives of this study were to develop regional, climatic zone rates of BNE from cropland in China and to assess the influence of environmental factors and management practices on BNE rates from cropland.

2. Materials and methods

2.1. N_2O emissions data

Data for field N_2O emissions from cropland in China were derived from peer-reviewed, published papers listed in the Web of Science, where N_2O measurements were field collected data, treatments were replicated at least three times, and accompanying soil background N_2O fluxes were reported; this process resulted in the extraction of data from 58 studies (see Supplementary material Table S1). Where they existed, proxies for missed soil properties values in the final dataset were obtained from the Harmonized World Soil Database (FAO, 2012) using the geographic location of the study (Zhou et al., 2017) (Table S2). All values for cumulative N_2O emissions were converted to kg N_2O-N $ha^{-1}yr^{-1}$. For agricultural fields where the climate was classified according to Zheng et al. (2010) and Wang et al. (2017), soil background N_2O emissions were grouped according to the main climatic zones in China into cool temperate (n = 2), middle temperate (n = 7), warm temperate (n = 12), north subtropical (n = 27), middle subtropical (n = 7), and south subtropical zone (n = 3) (Fig. 1). Thus, the dataset was not represented by equal numbers of field observations in different climatic zones. Other climatic zones, such as cold plateau and edge tropical zones, were not included due to lack of field data. Field crop data for each province were obtained from Zhang et al. (2014).

2.2. Data analysis

Emissions data (Table S2) were assessed for normality using the Shapiro-Wilk and D'Agostino kurtosis tests. A test for heterogeneity among the data from different regions was conducted and all datasets were squared-root transformed prior to analysis and modeling. Key

factors regulating BNE rates from cropland soils, using unfertilized treatments as a control, were determined using stepwise multiple linear regression of climate and soil physicochemical factors (Table S2) (Chen et al., 2014) and model fitness was evaluated using residuals analysis (Zou et al., 2007). We defined default values for soil BNE rate for the climatic zones to estimate regional and national soil BNE (RBNE, method one), and one (national) default value for soil BNE rate to estimate national soil BNE (NBNE, method two), along with the IPCC default value (method three). Statistical analyses were performed using a meta-analysis software in SPSS (SPSS 22.0) and Origin Pro 8.5.0 (Origin Lab Corporation, USA).

3. Results

3.1. Background emission rates of N_2O

The overall mean BNE rate from agricultural soils in the different regions was 0.93 kg N ha^{-1} yr^{-1} and ranged from 0.08 to 5.65 kg N ha^{-1} yr^{-1} (n = 58), where the highest (1.66 kg N ha^{-1} yr^{-1}) and lowest (0.53 kg N ha^{-1} yr^{-1}) rates were found in the north subtropical and cold temperate zones, respectively. BNE rates in the north and south subtropical zones were higher than those in temperate zones (p < 0.05; Fig. 2).

3.2. Factors affecting soil background N_2O emission rates

Mean BNE rate was highest in soils with total N (TN) content > 1 g N kg^{-1} (Table 1). Similarly, highest mean BNE rate (1.80 kg N ha^{-1} yr^{-1}) was found when soil pH ranged between 5.5 and 7.5, while lowest mean BNE rates of 0.79 and 0.76 kg N ha^{-1} yr^{-1} occurred when soil pH was > 7.5 and < 5.5, respectively. Regions with rainfall of 600–1200 mm yr^{-1} showed the highest rate of BNE, whereas lowest values were found where rainfall was > 1200 mm yr^{-1} and mean BNE rates were higher when mean annual air temperature was > 10 °C (Table 1). Mean BNE rate (1.43 kg N ha^{-1} yr^{-1}, n = 30) was higher from soils with soil organic carbon (SOC) content > 8 g C kg^{-1}, and was lower (1.04 kg N ha^{-1} yr^{-1}, n = 15) from soils with SOC content < 8 g C kg^{-1}. Soil C was correlated with TN (SOC = 0.093 T N + 0.052, R^2 = 0.76, n = 45, p < 0.05). Highest mean BNE rate (2.08 kg N ha^{-1} yr^{-1}) occurred in soils with bulk density > 1.4 g cm^{-3}, while the lowest mean rate was recorded from soils with bulk density of 1.2–1.4 g cm^{-3}. Highest mean BNE rate (1.86 kg N ha^{-1} yr^{-1}) was recorded from vegetable crops and the lowest BNE rate (1.15 kg N ha^{-1}

Table 1
Effects of soil physicochemical properties, crop types, and weather parameters on mean soil background N_2O emission rates from cropland in China.

Factor	Number of measurements[a]	Mean (kg N ha^{-1} yr^{-1})	95% Confidence intervals		SEM	p value
			Lower	Upper		
Total nitrogen (g N kg^{-1})						
< 1	23	0.94b	0.61	1.27	0.16	< 0.01
> 1	26	1.53a	0.90	2.15	0.30	< 0.01
Soil pH						
< 5.5	6	0.76b	0.44	1.09	0.13	< 0.01
5.5-7.5	22	1.80a	1.10	2.50	0.34	< 0.01
> 7.5	20	0.79b	0.46	1.13	0.16	< 0.01
Precipitation (mm yr^{-1})						
< 600	9	1.10a	0.43	1.77	0.29	< 0.01
600-1200	32	1.49a	0.96	2.00	0.25	< 0.01
> 1200	10	0.66b	0.38	0.93	0.12	< 0.01
Mean annual air temperature (°C)						
< 10	5	0.67b	0.40	0.94	0.10	< 0.05
10–20	42	1.34a	0.92	1.76	0.20	< 0.05
> 20	3	1.03a	–0.35	2.39	0.32	< 0.05
Soil organic carbon (g C kg^{-1})						
< 8	15	1.04b	0.54	1.54	0.23	< 0.05
> 8	30	1.43a	0.89	1.98	0.27	< 0.05
Bulk density (g cm^{-3})						
< 1.2	10	0.95b	0.38	1.52	0.25	< 0.05
1.2–1.4	12	0.73b	0.15	1.29	0.26	< 0.05
> 1.4	7	2.08a	0.32	3.84	0.72	< 0.05
Crop type						
Cereals	35	1.15b	0.79	1.50	0.18	< 0.05
Legumes	5	1.42ab	0.15	2.99	0.57	< 0.05
Vegetables	9	1.86a	0.45	3.26	0.61	< 0.05

Means followed by different letters within a column are different at p < 0.05.
[a] The difference in number was due to missing values in some studies.

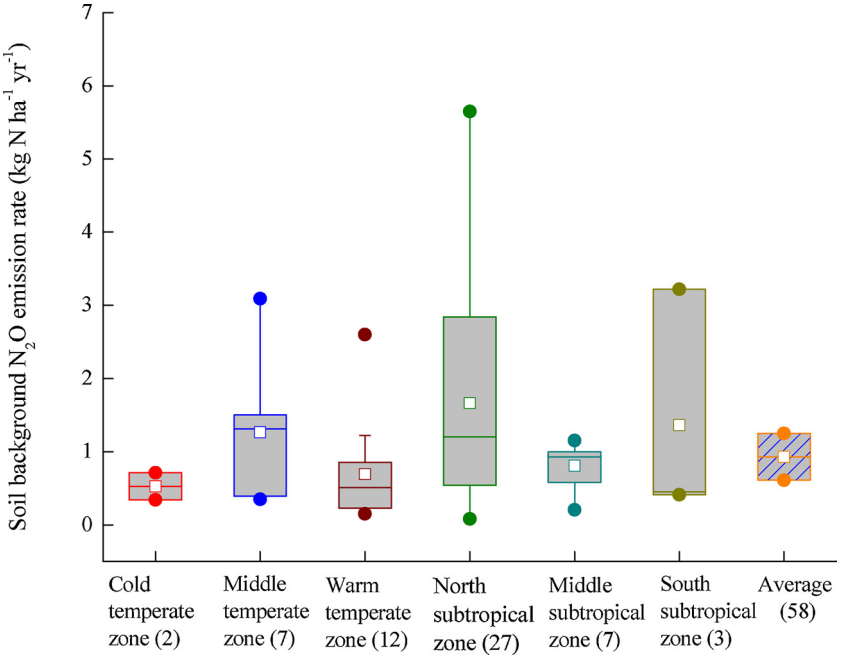

Fig. 2. Background N_2O emission rates from cropland soils in different climate zones in China. The dot, box, and whisker denote range, mean, and 95% confidence intervals, respectively, and values in parentheses are the number of replicates in each zone.

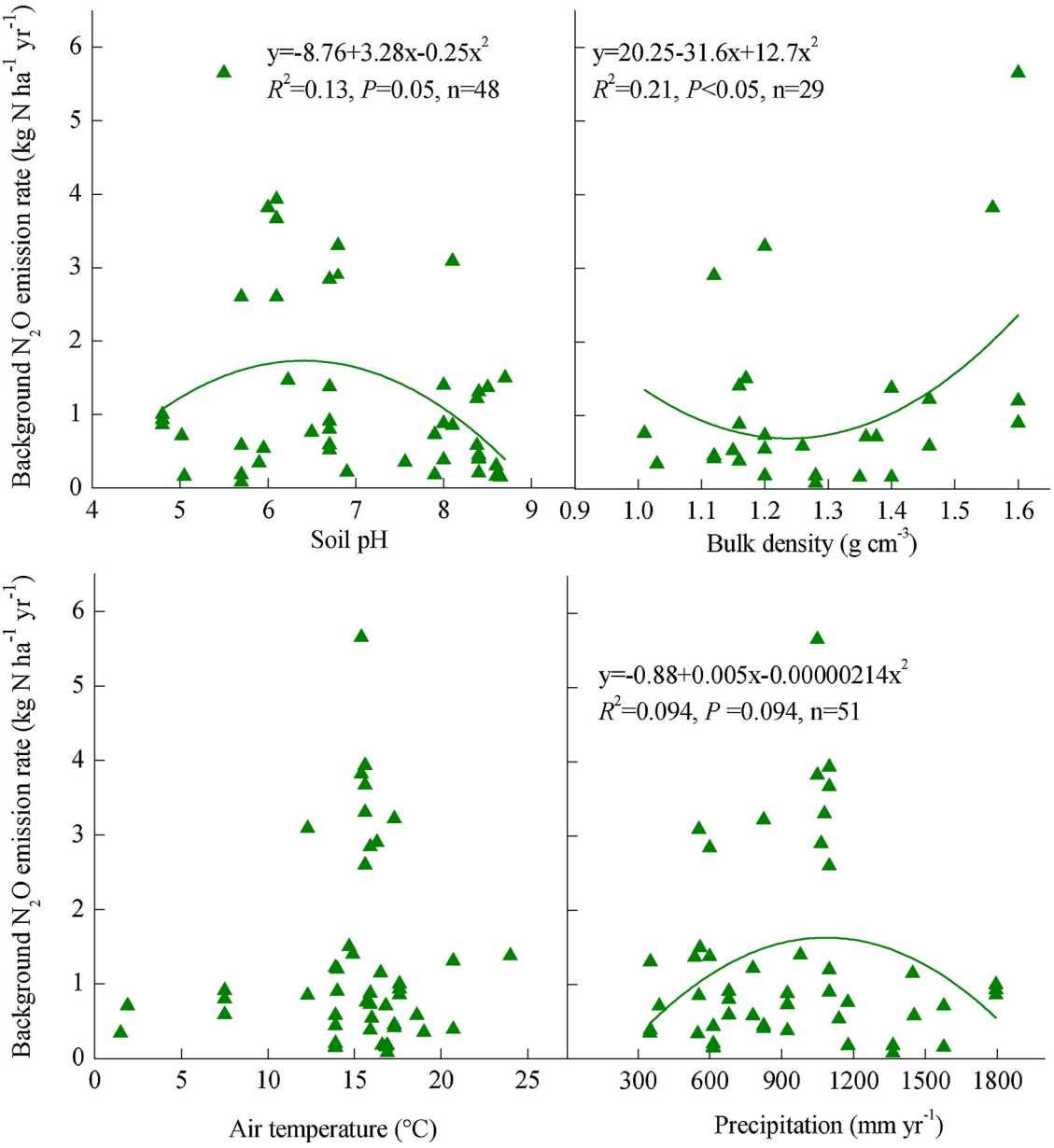

Fig. 3. Relationships between soil background N_2O emission rates and soil properties or weather parameters in croplands of China.

yr^{-1}) occurred in cereals (Table 1).

There were quadratic relationships between BNE rate and bulk density ($R^2 = 0.21$, $n = 29$, $p < 0.05$), and soil pH ($R^2 = 0.13$, $n = 48$, $p = 0.05$). A marginally significant quadratic relationship was also found between BNE rate and mean annual precipitation ($R^2 = 0.093$, $n = 51$, $p = 0.094$) (Fig. 3). Soil pH was significantly correlated with precipitation ($R^2 = 0.63$, $n = 43$, $p < 0.01$), while soil total N was significantly correlated with annual precipitation ($R^2 = 0.19$, $n = 45$, $p < 0.05$) and mean air temperature ($R^2 = 0.16$, $n = 44$, $p < 0.05$) (Fig. 4). Here, SOC was not included in our multiple linear regression model because of the autocorrelation we observed between SOC and TN. Stepwise, multiple linear regression predicted BNE rate (kg N ha^{-1} yr^{-1}) was as follows:

BNE rate = 3.3 + 0.07(TN) + 1.02(bulk density) − 1.05(pH) − 0.03(precipitation) ($R^2 = 0.45$, $n = 58$, $p < 0.01$).

3.3. Estimate of BNE from croplands in China

Using the default soil BNE rates for the climatic zones, total national BNE (known as RBNE) was estimated at 129 Gg N yr^{-1} and using one national default rate, total national BNE (NBNE) was 114 Gg N yr^{-1} (Table 2). The highest BNE was found in Heilongjiang (15.02 Gg N yr^{-1}) and Anhui (9.55 Gg N yr^{-1}) provinces (Figs. 5 and 6) representing 11.64% and 7.39% of the total national BNE, respectively (Table 2) and the lowest BNE was recorded from Beijing (0.17 Gg N yr^{-1}) and represented 0.13% of the total national BNE (Table 2). Among the regions, the highest BNE (32.66 Gg N yr^{-1}) was recorded from East and Central China, followed by Northeast China (24.88 Gg N yr^{-1}), representing 25.30% and 19.27% of the total national BNE, respectively. South China had the lowest BNE (11.42 Gg N yr^{-1}), contributing 8.84% of the total national BNE.

4. Discussion

4.1. Regional effects of climate

BNE rates from cropland soils varied among the climate regions in China, where they were highest in the north subtropical zone and

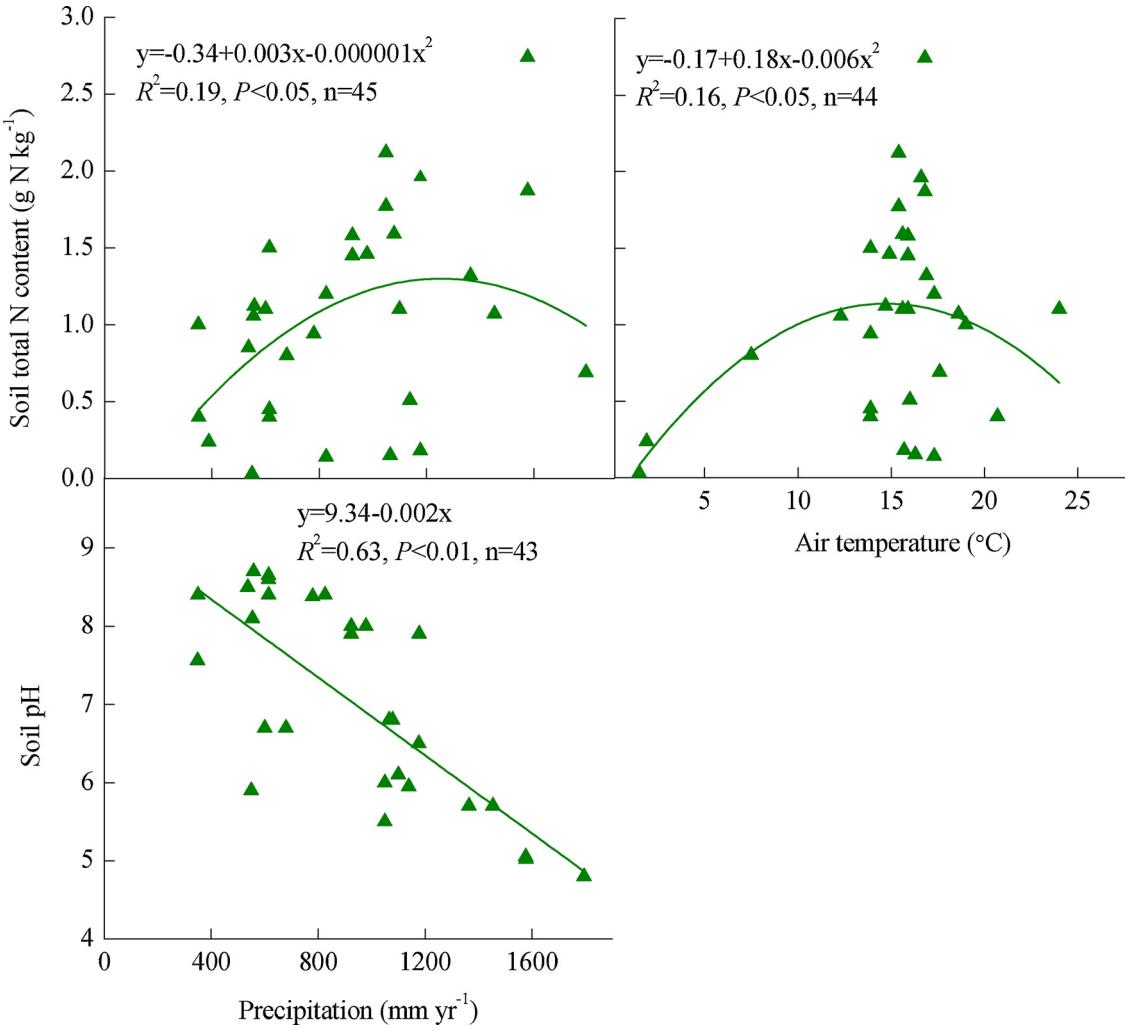

Fig. 4. Relationships between soil total nitrogen (TN) content and soil pH, and TN content and weather variables.

lowest in the warm and cold temperate zones. Bouwman et al. (2002) reported similar results for BNE rates that were higher in tropical than in temperate climates. It is possible that the high BNE rate in the north subtropical zone was due to the levels of precipitation (600–1200 mm yr^{-1}) and air temperature (14–16.9 °C) that approximated to values for optimal nitrification and denitrification processes (Granli and Bøckman, 1994; Curtin et al., 2012). Regression analysis showed a quadratic relationship between soil TN content, and by extension, emission of N_2O, and precipitation and temperature. In contrast, high levels of precipitation (> 1200 mm yr^{-1}) resulted in relatively lower BNE rates in the south subtropical zone, which may have been a consequence of a reduction in microbial activities under higher levels of soil moisture content (Ruser et al., 2006). We also found a negative relationship between annual precipitation and soil pH and it is likely that high levels of precipitation resulted in reduced nitrification and consequently reduced denitrification associated with low soil pH (Davidson et al., 2000). Gu et al. (2007) also observed that annual BNE rates were significantly correlated with annual precipitation at the narrow range of 540–1100 mm but not at the wide range of 530–1795 mm; however, they did not find significant effects of annual mean temperature upon annual BNE rates, as observed in this study.

Soil BNE rate in the mid-temperate zone was higher than that in the warm temperate zone and may have been caused by denitrification activity during the freeze-thaw cycle in winter (Kaiser and Ruser, 2000; Kim et al., 2012). For example, Chen et al. (2016) observed pulses in N_2O emissions during the spring melting period, when soil moisture content was greater than 67–76% water filled pore space, accounting for 20.1–49.4% of annual emissions. In contrast, the low BNE rate we found in the cold temperate zone was probably due to low mean annual air temperature and precipitation, as indicated by a study that reported low air temperatures weakened the relationship between SOC and BNE rate in wheat cultivation in China (Ding et al., 2013). Other studies have also shown that low temperatures decreased SOC decomposition, leading to a reduction in soil mineralized N (Brentrup et al., 2000; Hao et al., 2001; Ding et al., 2007a) available for N_2O production, Ni et al. (2012) and Chen et al. (2014) demonstrated that low N_2O emissions from cultivated black soils in the north-eastern China were due to low precipitation and temperature, as well as low levels of labile SOC.

4.2. Soil physicochemical and weather effects

The highest BNE rate occurred in soils with SOC content > 8 g C kg^{-1}, pH value of 5.5–7.5, and bulk density > 1.4 g cm^{-3}. Tiedje (1988) and Brentrup et al. (2000) found that increasing SOC increased the rate of soil BNE. The difference in BNE rate between soils with SOC content < 8 g C kg^{-1} and > 8 g C kg^{-1} was narrow, albeit significant, in this study, and the relationship coefficient between SOC and BNE rate was lower than that reported by Kim et al. (2013). Gu et al. (2009) demonstrated that cropland BNE partially originated from residual N that had been added during the previous cropping season. Thus, it is likely that residual N fertilizer, as a result of over-application in previous seasons to increase crop yields (Meng et al., 2017; Zhang et al.,

Table 2
Estimated soil background N_2O emissions from croplands by province in China.

Province	Climatic zone[a]	Cropland area (Mha)	N_2O emission (Gg N yr^{-1})		Contribution to national total (%)	
			RBNE	NBNE	RBNE	NBNE
North China	–	26.61	18.37	24.73	14.23	21.74
Beijing	WTZ	0.24	0.17	0.22	0.13	0.20
Tianjin	WTZ	0.44	0.30	0.41	0.24	0.36
Hebei	WTZ	6.36	4.39	5.91	3.40	5.20
Shanxi	WTZ	4.10	2.83	3.81	2.19	3.35
Shandong	WTZ	7.53	5.20	7.00	4.02	6.15
Henan	WTZ	7.94	5.48	7.38	4.24	6.49
Northeast China	–	21.46	24.88	19.95	19.27	17.53
Liaoning	WTZ	4.09	2.82	3.80	2.19	3.34
Jilin	MTZ	5.54	7.04	5.15	5.45	4.53
Heilongjiang	MTZ	11.83	15.02	11.00	11.64	9.66
East and Central China	–	24.06	32.66	22.36	25.30	19.65
Shanghai	NSZ	0.25	0.42	0.23	0.32	0.20
Jiangsu	NSZ	4.79	7.95	4.45	6.16	3.91
Zhejiang	MSZ	1.94	1.57	1.80	1.22	1.58
Anhui	NSZ	5.75	9.55	5.35	7.39	4.70
Jiangxi	MSZ	2.84	2.30	2.64	1.78	2.32
Hubei	NSZ	4.69	7.79	4.36	6.03	3.83
Hunan	MSZ	3.80	3.08	3.53	2.38	3.10
South China	–	9.17	11.42	8.53	8.84	7.50
Fujian	MSZ	1.34	1.09	1.25	0.84	1.09
Guangdong	SSZ	2.87	3.90	2.67	3.02	2.34
Guangxi	SSZ	4.23	5.75	3.93	4.46	3.46
Hainan	ETZ	0.73	0.68	0.68	0.53	0.60
Southwest China	–	19.26	19	17.9	14.72	15.73
Sichuan	SSZ	6.02	4.88	5.60	3.78	4.92
Guizhou	MSZ	4.53	3.67	4.21	2.84	3.70
Yunnan	SSZ	6.10	8.30	5.67	6.43	4.98
Chongqing	MSZ	2.25	1.82	2.09	1.41	1.84
Xizang	CPZ	0.36	0.33	0.33	0.26	0.29
Northwest China	–	21.85	22.78	20.31	17.64	17.85
Inner Mongolia	MTZ	7.24	9.19	6.73	7.12	5.91
Shaanxi	WTZ	4.14	2.86	3.85	2.21	3.38
Gansu	MTZ	4.69	5.96	4.36	4.61	3.83
Qinghai	CPZ	0.55	0.51	0.51	0.40	0.45
Ningxia	MTZ	1.12	1.42	1.04	1.10	0.91
Xinjiang	WTZ	4.11	2.84	3.82	2.20	3.36
National total	–	122.4	129	114	100	100

RBNE: soil background N_2O emissions estimated using different regional BNE rates; NBNE: soil background N_2O emissions estimated using the national BNE rate; CTZ: cold temperate zone; MTZ: middle temperate zone; WTZ: warm temperate zone; NSZ: north subtropical zone; MSZ: middle subtropical zone; SSZ: south subtropical zone; ETZ: edge tropical zone; and, CPZ: cold plateau zone.

[a] Climatic zones were based on Zheng et al. (2010) and Wang et al. (2017).

2017), reduced the contribution of SOC decomposition to available N due to increased inorganic N substrates, partially masking the relationship between SOC and BNE rate (Gu et al., 2013). A significant correlation between N_2O emissions and SOC has also been reported by Ciampitti et al. (2008), who suggested that SOC stimulated denitrification potential in soils by providing substrates for microbial activities (Bremner, 1997; Cameron et al., 2013).

The relationship we recorded between BNE rate and soil pH suggests that neutral soil pH may result in a high BNE rate. Bouwman et al. (2002) and Stehfest and Bouwman (2006) also reported that N_2O emission rates from cropping systems increased when soil pH increased from 5.5 to 7.3. In this study, the BNE rate in soils with pH $>$ 7.5 was low, probably due to a reduction in denitrification and/or a decrease in mineral N typical of soils with high pH (Alexander, 1977; Kim et al., 2013). Kim et al. (2013) suggested that SOC decomposition is higher at near-neutral pH and some studies (e.g. Bouwman et al., 2002; Gu et al., 2007; Dalal and Allen, 2008; Hernandez-Ramirez et al., 2009) have reported that high BNE rates at near-neutral pH were due to high heterotrophic nitrification rates. It is possible that the low emissions from acid soils observed in our study were due, in part, to low availability of labile organic C (Simek and Cooper, 2002).

We found a quadratic relationship between BNE rate and bulk density that has not been reported in other studies. Previously, highest BNE rates were generally found in soils with higher bulk density (Harrison-Kirk et al., 2015; Rabot et al., 2016) and it is known that increasing soil bulk density, such as through compaction, enhances potential denitrification (Cai et al., 2012). In contrast, we found that the lowest BNE rate was measured in soils where higher bulk density ranges from 1.2 to 1.4 g cm^{-3}. High bulk density soils are widely distributed on the North China Plain and Sichuan Basin (Gong et al., 2003), which, with a loam texture and low SOC content, may lead to low BNE rates. We found that soils with bulk density of $<$ 1.2 g cm^{-3}, such as black soils with higher SOC content and clay loam texture, which are mainly distributed in the cold temperate zone (Chen et al., 2016), had higher BNE rates, possibly due to high denitrification potential reported for clay soil types (Brentrup et al., 2000). Indeed, Tan et al. (2009) reported that N_2O emissions from clay loam soils were four times higher than from sandy loam soils, because anaerobic conditions in fine textured soils were more easily attained (Bouwman et al., 1993; Pelster et al., 2012).

We found that BNE rate increased with mean annual air temperatures up to 20 °C, but sharply decreased above 20 °C. This was probably due to the fact that drier soils associated with higher temperatures let to reduced N_2O fluxes (Liu et al., 2008; Lin et al., 2012). Granli and

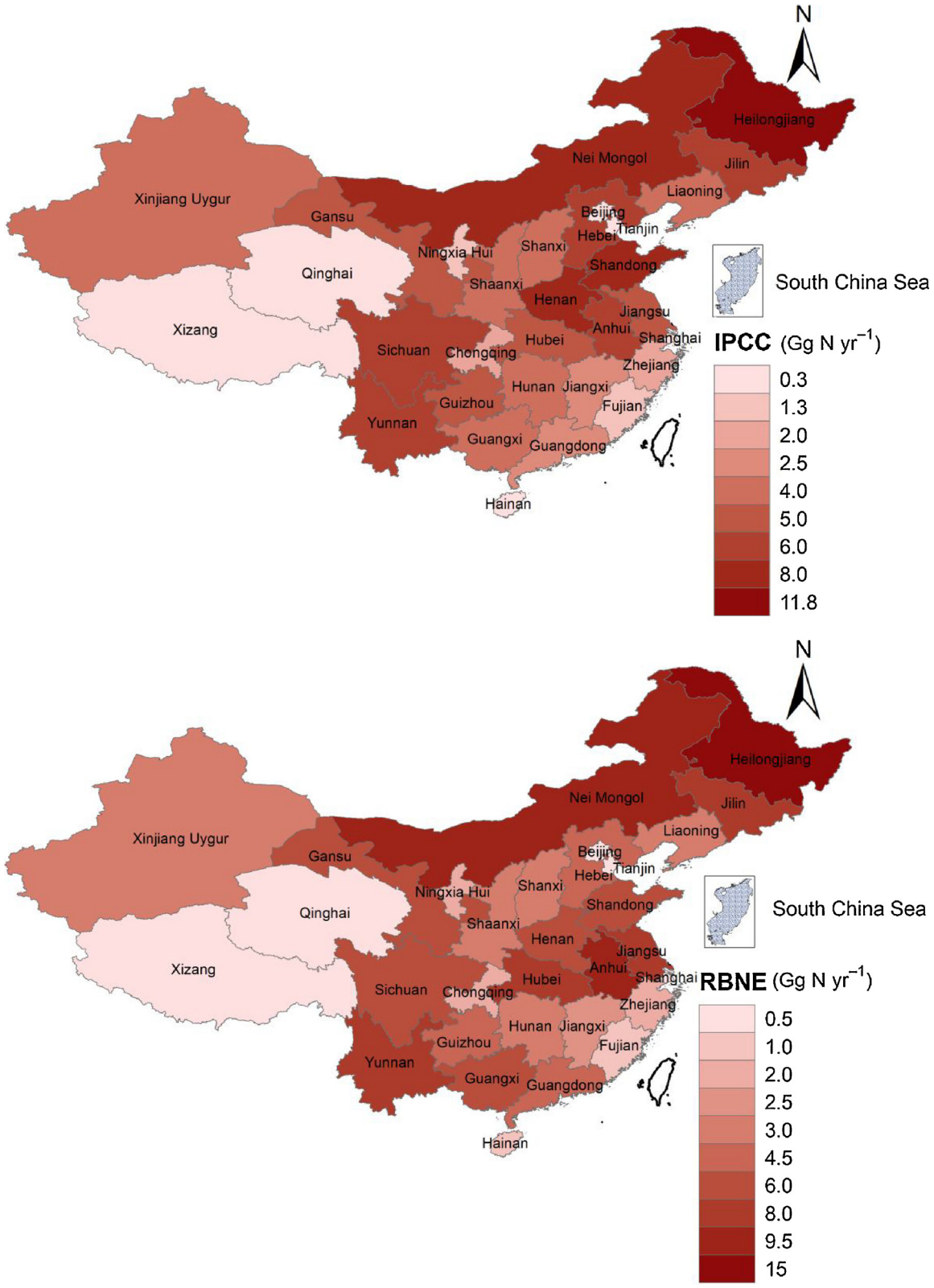

Fig. 5. Provincial pattern of soil background N_2O emissions estimated using one default value of BNE emission rate (IPCC) and regional emission rates (RBNE) based on cropland area in China (Gg N yr^{-1}).

Bockman (1994) suggested that temperature ranges of 25–40 °C are optimum for nitrification and denitrification processes, while Klotz (2011) reported optimum temperatures of 25–30 °C. BNE fluxes less than zero have also been reported when soil temperatures were below freezing points (Chen et al., 2014). Temperatures below 10 °C are known to reduce microbial activity and subsequently N_2O emissions (Holtan-Hartwig et al., 2002). The sharply reduced BNE rate with decreasing temperature that we observed was likely attributed to a decrease in nitrification rate. Low temperatures have been shown to reduce nitrification rates under wheat (Ding et al., 2007b) that may be

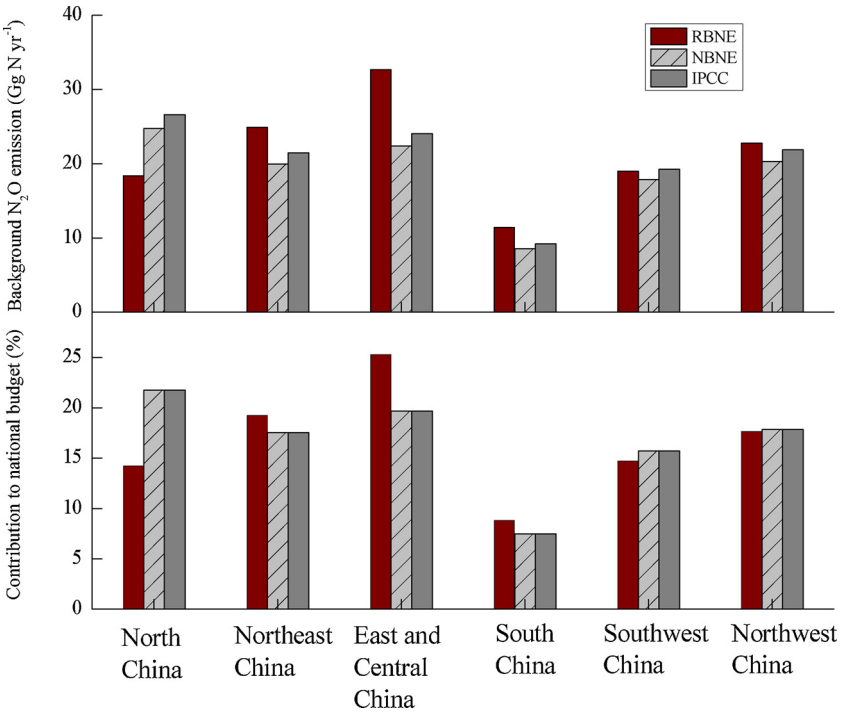

Fig. 6. Soil background N_2O emissions and contribution of different regions to total national budget in croplands in China.

associated with low mineralization rates of SOC under low temperature conditions (Davidson et al., 1998). The resulting low levels of mineral N have been shown to lead to low rates of nitrification and denitrification (Gödde and Conrad, 2000). Ding et al. (2013) observed that low temperatures suppressed SOC decomposition and reduced mineralized N in a wheat crop, leading to low N_2O emissions. It is possible that reduced activity of ammonia-oxidizing bacteria (AOB) at low temperatures (Dorland and Beauchamp, 1991; Liu et al., 2017) may have reduced nitrification and N_2O emissions (Lin et al., 2017) in our study, since low N_2O production induced by low temperatures may be a result of decreased NO_3^- availability (Dorland and Beauchamp, 1991). Indeed, low N_2O production rates have been attributed to low levels of NO_3^- (Chen et al., 2016) and Sehy et al. (2003) reported that N_2O production rates tended to be low when NO_3^- was reduced to below the threshold level of 3.5 mg N kg^{-1}. Holtan-Hartwig et al. (2002) observed that low temperatures favored the N_2O reduction process during denitrification and influenced the availability of O_2, NO_3^- and C substrates that are regarded as critical key factors in N_2O emissions (Glenn et al., 2012; Eyre et al., 2013; Chen et al., 2014, 2016).

In our analysis, we found that soil BNE rates were 1.10, 1.49, and 0.66 kg N ha^{-1} yr^{-1} when precipitation was < 600, 600–1200, and > 1200 mm yr^{-1}, respectively, indicating that precipitation of > 1200 mm yr^{-1} reduces BNE rate. These results concur with previous work that has shown that, along with high temperatures in tropical and subtropical zones, high levels of precipitation increase N leaching (Uchida et al., 2014) and induce the development of acidic red soils, thereby reducing nitrification and denitrification and consequently N_2O production.

4.3. Influences of crop types

The highest BNE rate from vegetable crops in our study supports previous findings (Wang et al., 2011; Chen et al., 2015). In Shandong Province, the application rate of N fertilizers to vegetable crops was found to be three-fold greater than to non-vegetables (Ma et al., 2000) and it is likely that the overloading of N fertilizer results in high levels of residual N in soil. For example, Ju et al. (2003) reported that nitrate stored in the upper 1 m soil profile of fields cultivated with vegetables in northern China amounted to 1410 kg N ha^{-1} and these levels could lead to an increase in BNE rate (Parkin et al., 2006; Hernandez-Ramirez et al., 2009; Gu et al., 2009). Yan et al. (2003) also found high BNE rates from vegetable fields derived from residual N from excessive N application, leading to the suggestion that vegetable cultivation contributes to high N_2O emissions in China (Wang et al., 2011). We found that BNE rate was higher from legumes than from cereals, probably as a result of their ability to fix atmospheric N_2 and release N into the soil (Rochette and Janzen, 2005). Eichner (1990) reported that N_2O emission rates from soils cultivated with legumes ranged from 0.34 to 4.6 kg N ha^{-1} yr^{-1} and Zhong et al. (2009) observed similar average N_2O emissions of 2.4 kg N ha^{-1} yr^{-1}, with a range of 1.9 to 2.9 kg N ha^{-1} yr^{-1}. In this study, the lowest BNE rate was found in cereal fields, similar to findings in Mediterranean cropping systems by Cayuela et al. (2017), likely as a result of the longer growth season and higher N uptake in cereals (Stehfest and Bouwman, 2006).

4.4. National scale soil background N_2O emissions

The mean national soil BNE rate was estimated at 0.93 kg N ha^{-1} yr^{-1}, which was lower than the global average (1.52 kg N ha^{-1} yr^{-1}) reported by Kim et al. (2013) and lower than those from Germany, Japan, Netherlands, and Denmark, but higher than those reported from France, Russia, Spain, and the UK (Table 3).

Using the default regional BNE rates, we estimated that the total national BNE budget from cropland soils in China was 129 Gg N yr^{-1}, which represented 28.5% of total N_2O emissions (323.8 Gg N yr^{-1}) reported from croplands in China that had been fertilized with inorganic N (Zhou et al., 2015). This proportion is within the range of 26–30% previously reported for ratio of BNE to total cropland N_2O emissions in China (Gu et al., 2009) and 20–53% previously reported for the relative contribution of soil BNE to the total national annual N_2O emissions from fertilized fields (Zheng et al., 2004). Other studies have reported a much wider range of BNE (10–52%) from agricultural fields (Brown et al., 2002; Yan et al., 2003; Gu et al., 2009; van Beek et al., 2011). Our estimate was close to levels suggested from arable soils in China by Kim et al. (2013) (131 Gg N yr^{-1}), Yan et al. (2003) (127.1 Gg N yr^{-1}), and Gu et al. (2007) (136 Gg N yr^{-1}), but higher than the

Table 3
Soil background N_2O emission rates from croplands in different countries.

Country	N_2O emission rate (kg N ha^{-1} yr^{-1})	Estimation method	Reference
China	0.93	Summary of available data	This study
China	1.07	Summary of available data	Kim et al. (2013)
China	1.23	Maximum likelihood model	Wang et al. (2011)
Australia	1.25	Summary of available data	Kim et al. (2013)
Canada	1.15	Summary of available data	Kim et al. (2013)
Denmark	2.95	Summary of available data	Kim et al. (2013)
France	0.11	Summary of available data	Kim et al. (2013)
Germany	1.27	Summary of available data	Jungkunst et al. (2006)
Japan	2.20	Summary of available data	Kim et al. (2013)
Netherland	4.56	Summary of available data	Kim et al. (2013)
Russia	0.39	Summary of available data	Kim et al. (2013)
Spain	0.10	Summary of available data	Kim et al. (2013)
Sweden	1.03	Summary of available data	Kim et al. (2013)
UK	0.64	Summary of available data	Kim et al. (2013)
USA	0.93	Summary of available data	Kim et al. (2013)

budgets estimated using the IPCC default value (122 Gg N yr^{-1}) and the national BNE rate (114 Gg N yr^{-1}) in this study. We argue that estimations of BNE using the single national rate may result in greater errors and biases. Our finding is similar to the result that measured N_2O emission in Corn Belt, United States was 420 Gg N yr^{-1}, a value that was larger than 230 Gg N yr^{-1} estimated using the IPCC default value (Griffis et al., 2013). Bouwman (1996) acknowledged that the use of a single BNE default value of 1.0 kg N ha^{-1} yr^{-1} may not be sufficient for BNE estimations on a global scale or in specific regions, due to scaling errors (Brown et al., 2001; Jungkunst et al., 2006; Tian et al., 2012; Zhu et al., 2013). Our analysis confirms that the BNE for specific regions differs from the default value of 1.0 kg N ha^{-1} yr^{-1}. Although north China had the largest cropland area (26.61 Mha), annual BNE was lower, at 18.4 Gg N yr^{-1}, representing 14.2% of the total national budget, whereas the 24.06 Mha of croplands in east and central China had the highest BNE of 32.7 Gg N yr^{-1}, representing 25.3% of the national croplands BNE budget.

Taking the default regional BNE rates into account greatly improved BNE estimates from croplands compared with only a mean national soil BNE rate; however, our estimate might have high uncertainties. First, uncertainties might arise from the different sampling frequency of the N_2O flux measurement in different field measurements (Zheng et al., 2004), since N_2O was generally emitted in pulses (Smith and Dobbie, 2001; Ju et al., 2011; Chen et al., 2016). Second, no data in the literature were available in the cold plateau and edge tropical zones (Wang et al., 2011) and the national average BNE rate was used for estimation in this study, which in turn increased the uncertainty of estimated soil BNE. Third, BNE rates were greatly affected by the type of crop and tillage practices (Bouwman et al., 2002). It is expected that the current estimation could be better improved when a considerable number of field measurements are available in the different climatic zones especially in the cold plateau zone in the future.

5. Conclusions

BNE rates varied among the different climatic zones in China, where highest rates were recorded in the north subtropical zone. Soil bulk density had greater influences on BNE rate than other soil variables. The soil BNE rate was higher under vegetable crops than under legumes and cereals. The total BNE budget for croplands in China was 129 Gg N yr^{-1} using different regional BNE rates. East and Central China regions had the highest BNE, while the lowest BNE was found in the South China. Our results showed that the IPCC projections using the single national default value did not accurately estimate soil BNE from croplands in China and we suggest the IPCC guidelines should be revised.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2018.08.003.

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